Chapter 13

Partitioned Aquaculture Systems

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Competition for land and water resources is driving the need to increase productivity of fish and shellfish aquaculture. At the same time, the public demands reduced environmental impact while expecting high-quality products from aquaculture. Simultaneously, strong international competition continues to force producers to seek ways to reduce production costs. Consequently, pond aquaculture, like other areas of agricultural production, is increasingly pushed to intensify and industrialize.

The conventional aquaculture pond provides a number of ecological services supporting fish and shellfish production. As described in chapter 10, the pond provides confinement space for the aquatic organisms, while algal growth in the pond serves as the base of an aquatic food chain providing some or all of the feed, depending on pond carrying capacity. In addition, algal growth removes potentially toxic CO_2 and ammonia from the pond environment and supplies needed oxygen. Other microbial, as well as physical and chemical, processes assist in treatment of metabolic waste produced by the aquatic animals. In most ponds these functions occur simultaneously in the same space where the animals are cultured as they are allowed to roam freely within the pond. The space required for animal confinement is much less than the area or volume needed to support the waste treatment functions. Consequently, combining animal-confinement and ecosystem support into the same physical space often leads to inefficiencies and management difficulties.

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Intensification of pond aquaculture beyond approximately 1,000 kg/ha requires that in-pond processes be enhanced or supplemented. Applying feeds produced outside the pond environment is the primary technique. Increased feed application rate increases oxygen demand beyond what can be supplied by passive diffusion and pond photosynthesis. Therefore, mechanical aeration is commonly employed to support production intensification. In addition to supplemental feeds and aeration, other techniques to intensify pond culture have been attempted. Crowding of fish into cages or raceways, management of pond sediment, and mixing and treatment of the water column have been attempted with varying degrees of success. In-pond raceways (chapter 15) provide many of the advantages of raceway culture but do not address the increased pond nitrogen loading, and, as a result, fish yields are similar to conventional pond culture. Nitrifying filters like those used to support indoor recirculating systems have been installed, but they are too expensive for large-scale commodity fish production. Investigators have also tried removing and treating pond sediments in attempts to increase fish production by reducing pond ammonia loading and oxygen demand. Water column flocculation has been studied as a technique to reduce the solids content of pond discharge water. Water column mixing was investigated in the late 1970s as a way to better utilize oxygen production capacity of algal growth in fishponds (Busch 1985). Fish polyculture has been shown to increase yields in ponds as a result of the stabilizing effect of algal cropping provided by filter-feeding fish.

Supplementation of ecological services and improved culture practices enabled increased pond catfish production from around 1,100 to 1,700 kg/ha in the early 1960s to typical industry production levels of 3,400 to 5,600 kg/ha by the 1980s (fig. 13.1). In 1959, Swingle recommended a maximum daily feeding rate of 34 kg/ha-d feed to avoid low dissolved oxygen in ponds, limiting pond

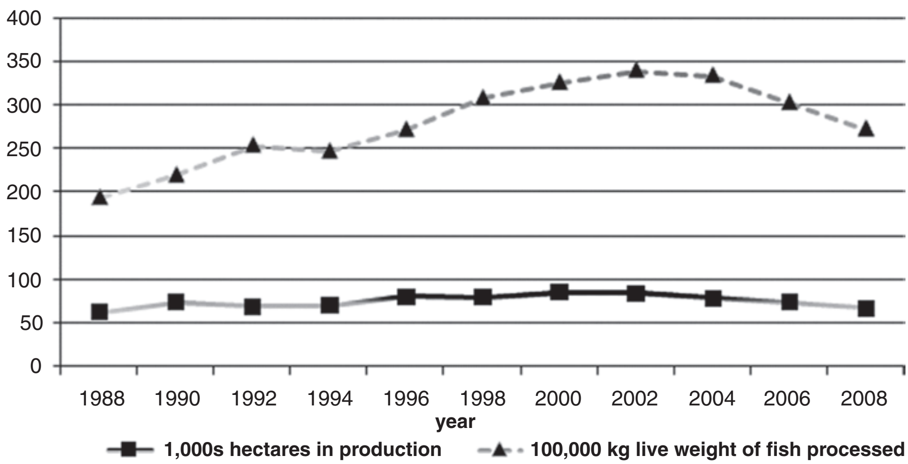


Figure 13.1 Relative increases in pond area and weight of fish processed during the period 1982 to 2002 (from Hargreaves and Tucker 2004).

production to around 1,100 kg/ha (1,000 lb/ac). In 1979, Tucker *et al.* presented data suggesting 3,000 to 4,800 kg/ha catfish production was possible, and by 1984, Busch reported on productivities ranging from 5,000 to 8,000 kg/ha in 1.6 ha (3.5 ac) ponds in Mississippi. In 2004, Hargreaves and Tucker observed that catfish farmers were stocking at rates of 10,000 to 15,000 fish/ha at typical catfish harvest size of 0.68 kg suggesting 6,700 to 10,100 kg/ha (6,000 to 9,000 lb/ac) production. Feed application and supplemental pond aeration are the primary, but not only, techniques enabling these increases. Many other factors interact to define the ceiling of fish yields from ponds, including fish diseases, processing plants' demand for fish, and feed quality and conversion efficiency, to mention a few. In spite of these interacting limitations, as fish-farmers are provided improved techniques to increase pond waste treatment capacity, in particular pond nitrogen removal, the aquaculture industry typically experiences slow but sustained across-the-board increases in fish yield.

By 1995, Clemson researchers had built and operated 0.13 ha (1/3 acre) prototypes of the partitioned aquaculture system (PAS), a technique in which conventional fishpond function is enhanced by installation of slow-moving paddlewheels and fish raceways. This technique represented an adaptation of the "high-rate pond" developed at University of California-Berkeley in the 1960s for treatment of municipal wastewater. The primary advantage provided by the high-rate pond and PAS is to increase algal production within the pond, accelerating ammonia assimilation and oxygen production. The PAS combines the advantages of the high-rate pond with other aquaculture intensification techniques. Of particular importance is the use of tilapia coculture allowing for manipulation of algal population, algal density control, and reductions in zooplankton numbers. As early as 1996 Clemson had successfully demonstrated 11,230 kg/ha (10,000 lb/ac) catfish production, and by 1998, 18,000 kg/ha (16,000 lb/ac) catfish production in six 0.13-ha PAS units. Ultimately, 42,000 kg of catfish and 4,500 kg of tilapia coproduction would be demonstrated in a 0.8-ha PAS prototype at Clemson.

Later, researchers focused on increased mixing and aeration in conventional ponds in an attempt to induce higher rates of waste treatment and fish production capacity in lower-cost conventional pond configurations. Torrans (2005) demonstrated 23,500 kg/ha (20,900 lb/ac) of catfish production in 0.1 ha (1/4 ac) intensively aerated/mixed (at 4 hp/ha) and managed experimental ponds. However, this approach is limited by difficulties encountered when attempting to scale intensive aeration/mixing to larger ponds.

The objective of Clemson University's PAS research program was to stimulate development of a sustainable aquaculture industry, providing a scalable technology enabling increased production with reduced environmental impact, while simultaneously increasing profitability. The PAS technology provides the potential for lower fish production unit-costs and higher productivity as compared to conventional earthen pond production. Subsequent investigators have concentrated on developing lower-cost modifications of the PAS. The Mississippi "split-pond," the Alabama "in-pond raceway," and the California "pondway," represent lower-cost or alternative adaptations of the PAS. The goal of these

modifications was to provide a lesser degree of pond ecological enhancement (as compared to the PAS), at minimal additional cost over still water pond culture.

13.1 High rate ponds in aquaculture—the partitioned aquaculture system

By the early 1980s pond-based fish farmers were facing a number of emerging issues including environmental impacts of pond discharge upon public surface waters, a pond productivity "ceiling" of 4,000 to 6,000 kg/ha, maximum pond feed loading of 112 kg of feed/ha-d (100 lb/ac-d), and low dissolved oxygen events driven by zooplankton infestations and cyclic algal blooms and crashes. Other limitations and concerns included labor requirements for fish harvesting and sorting requirements, fish feed conversions of 2.0 to 2.2:1, fish flesh off-flavor events limiting sales, and bird and mammal predation losses, all of which negatively impact fish production and profitability.

Algal biosynthesis is the primary process controlling ammonia concentrations in aquaculture ponds. Algal production in a typical unmixed aquaculture pond is limited to 1 to 3 g-C/m^2-d corresponding to 0.5 mg/L-d of N addition, which is roughly equivalent to a feed loading of 90 to 112 kg/ha-d, limiting pond fish production at the 4,000 to 6,000 kg/ha per season.

In the 1960s, William Oswald and coworkers at the University of California Berkeley developed the use of low RPM paddlewheels to increase algal growth in ponds for use in treating municipal wastewater—a technique called "the high-rate pond." The partitioned aquaculture system (PAS) developed at Clemson University from 1988 to 2008 represents a high-rate pond adapted to expand the carrying capacity of pond aquaculture by increasing the rate of ammonia assimilation through enhancement of algal growth. In addition, the PAS combines a number of previously developed aquaculture intensification techniques into a single integrated system increasing operator control over pond culture processes. Initially in 1988, four 100 m^2 (1/4 ac) pilot-scale PAS units were installed and operated at Clemson University's Calhoun Field Station facility. Beginning in 1997, six 0.13 ha (1/3 ac) PAS were installed, and, later, a single 0.8 ha (2 ac) PAS was installed; these were operated for channel catfish production trials.

The concept of the PAS is to partition fish pond culture into separate physical, chemical, and biological processes linked together by a homogenous water velocity field (fig. 13.2). The physical separation achieves two important goals. First, it allows researchers to precisely quantify the fish culture and pond ecosystem processes. Second, separating the fish culture operation from the "at-large" algal production and water treatment function of the pond allows independent optimization of the processes thereby enhancing and maximizing performance of each component.

The PAS design consists of three physical components: the algal channels with paddlewheel, the fish raceways (with or without a separate paddlewheel) separated from the algal ponds with coarse screens, and a settling sump, to

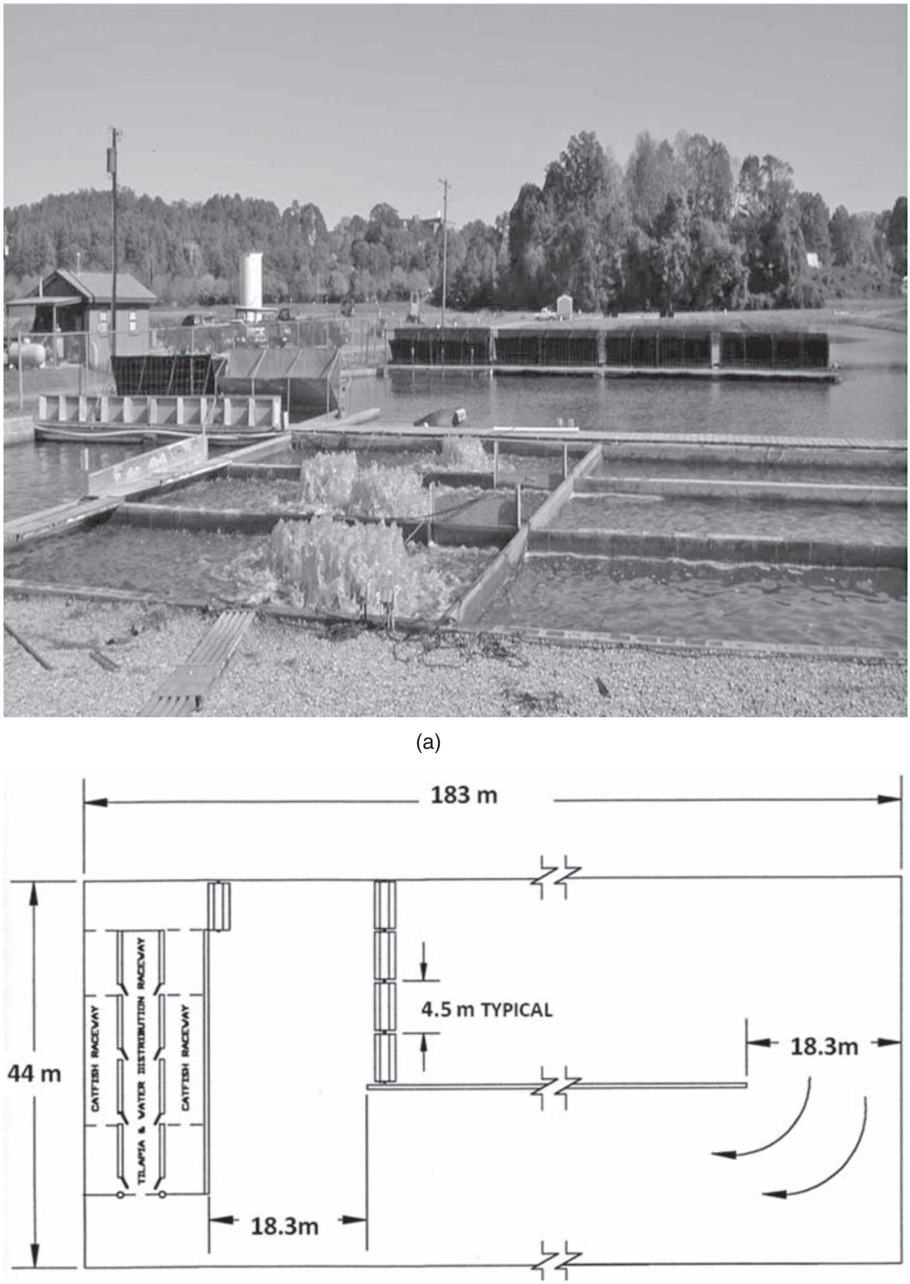


Figure 13.2 Photograph (a) and schematic (b) of two-acre partitioned aquaculture system showing algal and fish-raceway paddlewheels.

capture and concentrate settleable solids (fish wastes and algal flocs) for removal from the system. In addition, the Clemson PAS included populations of caged or free-roaming tilapia and, in some cases, a separate algal harvesting process for removal of algal biomass production.

The PAS takes advantage of accelerated algal growth potential provided by the high-rate pond observed by Oswald (1988, 1995) and colleagues at the University of California in treatment of municipal wastewater (Benemann 1997; Benemann *et al.* 1980; Green 1994) and is now used by most algal production companies (Benemann & Weissman 1993). The driver of the system is the low-speed paddlewheel that moves water in a racetrack configuration. Paddlewheel-mixed algal growth ponds had not previously been used in aquaculture production. The velocity imparted by the paddle ensures a mixed water column, increasing effective exposure of algal populations to solar radiation thereby increasing pond primary production. This configuration maximizes algal ammonia-N and CO_2 uptake, enhances interfacial gas exchange, minimizes waste solids settling in the pond, and provides an opportunity to harvest excess algal solids. These features improve pond water quality while providing biomass for algal byproducts or for use as a potential bioenergy resource.

13.1.1 Paddlewheels for water movement

The paddlewheel is the central design element transforming the still water fishpond into a high-rate pond with raceway fish culture. Turning at 1 to 3 rpm, the paddlewheel imparts a water velocity field throughout the algal section and fish raceways. The uniform water velocity field reduces dead zones ensuring that the entire water column is utilized for algal growth and waste treatment. In 0.8-ha units, the paddles were constructed from 16 to 18 gauge mild-steel sheets welded to 0.85 cm (2 inch) schedule 40 steel pipe used as a shaft and supported on standard pillow-block bearings. Bearing failure lead to replacement of pillow-blocks with bearings machined from Teflon. One-piece Teflon bearings provided longer life at lower cost and were easier to replace. Angle-iron struts were welded at the end of the blades to prevent excessive flexure of paddle-blades at the shaft weld joint. Stainless steel should be avoided in this application as flexing of brittle stainless construction materials results in failure of blades and shafts. Typical power requirements at paddlewheel scales examined ranged from 0.75 to 1.13 KW/ha (1.0 to 1.5 hp/ac). Field studies suggest that water velocities ranging from 0.03 to 0.09 m/sec (0.1 to 0.3 ft/sec) are adequate for fish production, while 0.09 to 0.15 m/sec (0.3 to 0.5 ft/sec) are needed if a higher level of algal productivity is desired. At the lower velocities, algal biomass will settle onto the pond bottom increasing benthic oxygen demand and ammonia production. At higher water velocities, (0.15 m/sec or greater) the paddles demand excessive horsepower, and increased water velocity erodes unlined pond berms and bottoms. In field operations paddlewheels were successfully driven using either oil hydraulic motors or variable frequency electrical drives.

13.1.2 Algal production

The most important difference between conventional pond aquaculture and the PAS is the increased algal growth achieved as a result of the increased mixing and uniform water velocity field. The threefold to fourfold increase in pond photosynthesis provides the basis for an increased sustainable feed application rate that supports a threefold to fourfold increase in fish carrying capacity and production.

Stoichiometry of algal biosynthesis in the PAS is similar to that reported by previous investigators (Shelef & Soeder 1980), with minor adjustments in the C:N and C:O_2 ratios observed in the PAS algal biomass production. The adjusted stoichiometry was field determined by Meade as:

$$106\ CO_2 + 16\ NH_4 + 52\ H_2O = C_{106}H_{152}O_{53}N_{16}P + 106\ O_2 + 16\ H \qquad (1)$$

The oxygen yield of 2.67 gm-O_2/g-C fixed suggests a 1:1 photosynthetic oxygen to carbon molar ratio. Average algal composition was observed to be approximately 50% carbon (by weight) yielding a C:N weight ratio of 5.7:1 and N:P weight ratio of 7:1.

As suggested by equation 1, harvest and removal of algal biomass from the pond environment using algal sedimentation and removal, or harvest and conversion into filter-feeding animal flesh, yields a net oxygen addition to and net nitrogen removal from the water column. The increased fish carrying capacity of the PAS is provided by the increased rates of nitrogen removal from, and O_2 addition to, the pond environment. This impact was dramatically demonstrated in observed differences in pond ammonia nitrogen concentrations in PAS units fed at similar levels as conventional ponds controls. At feed application rates ranging from 56 to 225 kg/ha-d (50 to 200 lb/ac/d), ammonia levels exceeded 16 mg/L in conventional ponds as opposed to just under 5 mg/L in PAS units (fig. 13.3). PAS field studies demonstrated sustained algal productivities of 6 to 12 g-C/m^2-d throughout the growing season, as opposed to 1 to 3 g-C/m^2-d observed in conventional aerated control ponds (Brune 1991; Brune *et al.* 2001a; Brune *et al.* 2003; Drapcho 1993; Drapcho & Brune 2000). The accelerated photosynthesis provides enhanced fish production per unit of pond area and water volume at significantly reduced aeration energy levels.

13.1.3 Raceway fish culture

The Clemson 0.8-ha (2 ac) PAS prototype was originally designed to include a three-channel raceway with the central channel delivering water into two "side-flow" fish raceways (fig. 13.4). With this configuration water flow enters the raceways as a "distributed plug flow." Adjustable gates are positioned to allow water flow to enter the raceway in proportion to the fish oxygen demand of individual containment cells (D_1 to D_4, as in fig. 13.4). Water velocity in the fish raceways is maintained using a separate paddlewheel. A separate paddle provides

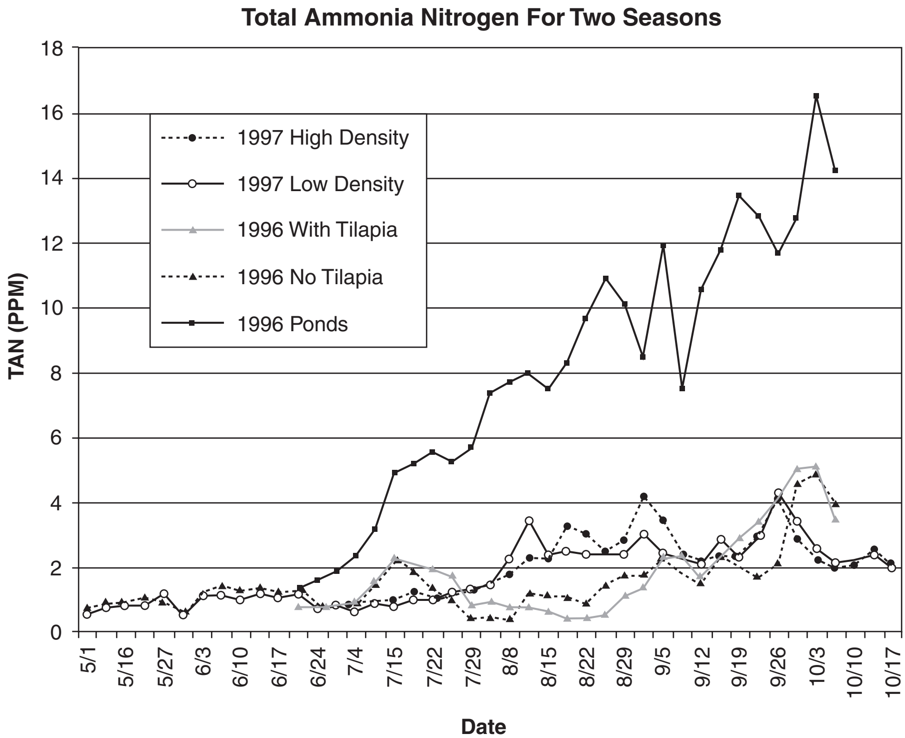
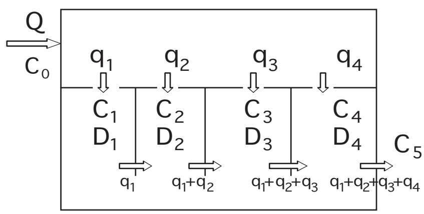


Figure 13.3 Ammonia nitrogen concentrations vs. time in conventional ponds and PAS units at feed application rates ranging from 56 to 225 kg/ha (50 to 200 lb/ac-d).

raceway oxygen and ammonia concentration independent of velocity or water quality in the larger algal basin. High fish density in the individual raceways provides scouring and rapid removal of waste solids. Side-flow raceways were found to be more cost effective than mixed tanks or mixed-loop tanks, the alternative design frequently used to provide uniform water quality to high density fish culture.



$$\frac{q_n}{D_n} = \frac{Q}{\Sigma D_n}, C_n = C_5 = \frac{\Sigma D_n}{\Sigma q_n}$$

Distributed plug flow

Figure 13.4 PAS side-flow raceway water delivery rate in proportion to fish oxygen demand providing uniform oxygen concentrations in fish cages arranged in series.

In 1999, fish culture at variable stocking densities showed that catfish biomass of 128 to 160 kg/m^3 (8 to 10 lb/ft^3) could be sustained within the raceways with no adverse effect on growth. This led to further reductions in system costs by using a single high-density side-flow raceway requiring fewer paddlewheels (Brune *et al.* 2004a). Results from these trials suggest that the lower cost configuration using a single fish raceway and single paddlewheel providing raceway water velocity control would be successful.

In addition to providing greater control of water quality, raceway fish culture was found to offer many other advantages over conventional pond culture. Since the growing fish can be more conveniently sorted and held as similar-sized cohorts in cells or cages, feed application may be fine-tuned to the individual fish weight. As a result, overall feed conversion efficiencies were improved from 2.0 to 2.2:1 (typically observed in pond culture systems) to 1.4 to 1.5:1 in the PAS. Inexpensive netting can be stretched across the top of raceway sections thereby completely eliminating avian fish-predation. Labor requirement for harvesting higher density cells is reduced over conventional ponds seining. And, application of drugs or vaccines is more effective in high-density raceways. In Clemson PAS growth trials, oxygen sensors were added to the fish raceways, making it possible to use the output signal from DO meters to provide feedback control of paddlewheel speed and raceway aerator function, enhancing operator control over fish dissolved oxygen exposure. Computer control of algal basin water velocity (paddlewheel rotation) allows for improved control of pond gas transfer rates providing optimum O_2 and CO_2 transfer throughout the day-night cycle.

13.1.4 Fish carrying capacity and production

From 1995 to 2000, a range of fish stocking rates, sizes, and species combinations were used to test the limits of the PAS carrying capacity (table 13.1). Field data confirmed the PAS capability of threefold to fourfold increases in water treatment capacity over conventional ponds (Brune *et al.* 2001b, 2003, 2004b; Brune 1997; Brune & Wang 1998; Schwartz 1998; Meade 1998). Improvements in water quality dynamics and reduced aeration requirements as a result of tilapia coculture established the technique as standard practice. By 1997, maximum feed application reached 236 kg/ha (210 lb/ac-d) at average seasonal feed application rates of 106 kg/ha-d (94 lb/ac-d). In 1998, average feed application rate was increased to 127 kg/ha (113 lb/ac-d) with maximum feed application exceeding 236 kg/ha (210 lb/ac-d). At this time, fish carrying capacity averaged 18,757 kg/ha (16,694 lb/ac). By 1999, net annual catfish production exceeded maximum carrying capacities as a result of implementation of end-of-year catfish cohort carryover. Loss of carryover fish from proliferative gill disease (PGD) in winter carryover fish limited 1999 production to 12,892 kg/ha (11,474 lb/ac) average production. At this time, the 0.8 ha system yielded 16,682 (14,847 lb/ac) net production. By 2000, annual net catfish production from all units averaged

Table 13.1 PAS catfish and tilapia stocking rates (kg/ha) for the 1995 to 2000 growing seasons.[1]

PAS unit	Area (acres)	1995	1996	1997	1998	1999	2000
1	0.13	477 C	933 C 253 T	1,538 C 933 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB	2,376 C 2,245 CC 126 TB
2	0.13	500 C	933 C 353 T	1,538 C 933 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB	2,376 C 2,245 CC 126 TB
3	0.13	500 C	933 C 353 T	1,538 C 933 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB	2,376 C 2,245 CC 126 TB
4	0.13	500 C	933 C 0 T	1,538 C 1,891 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB 1,538 T	2,376 C 2,245 CC 126 TB
5	0.13	500 C	933 C 0 T	1,538 C 1,891 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB 1,538 T	2,376 C 2,245 CC 126 TB
6	0.13	500 C	933 C 0 T	1,538 C 1,891 T	2,458 C 1,389 T	2,178 C 4,056 CC 271 TB 1,538 T	2,376 C 2,245 CC 126 TB
Large	0.81					3,012 C 933 T 89 TB	2,926 C 155 TB

[1] C = catfish fingerlings; T = tilapia fingerlings; TB = tilapia breeding pairs; CC = catfish carryover.

19,362 kg/ha (17,232 lb/ac) with a maximum carrying capacity of 15,852 kg/ha (14,108 lb/ac) and a tilapia coproduction of 6,075 kg/ha (5,407 lb/ac).

By 1996, at an average fish carrying capacity of 10,000 kg/ha, the importance of coculture of catfish with tilapia was already evident. During 1997, an optimum end-of-season tilapia/catfish biomass ratio of 1:4 was established at catfish carrying capacities of 15,700 kg/ha. By 1998, 19,000 kg/ha catfish production using multiple stockings was demonstrated. Catfish production increased over the seven years of field trials in both large and small units ultimately peaking at an average of 20,225 kg/ha (18,000 lb/ac; fig. 13.5). Peak feed application rates were demonstrated to be sustainable at 280 kg/ha (250 lb/ac-d) with seasonal averages exceeding 157 kg/ha (140 lb/ac-d).

13.1.5 Stabilizing algal populations with tilapia coculture

Work at Clemson focused primarily on stocking the Nile tilapia, *Oreochromis niloticus,* into the PAS for use as an algal stabilizing technique. Kent SeaTech

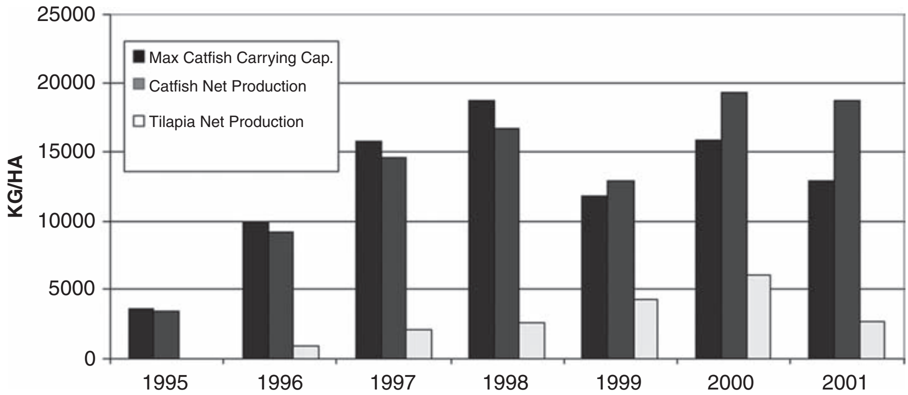


Figure 13.5 Clemson University PAS channel catfish and tilapia net production from 1995 to 2001.

Corporation in southern California used the Mozambique tilapia, *Oreochromis mossambicus,* and its hybrids. Tilapia is a tropical species, which leads to certain disadvantages for year-round use in the southern United States. Although tilapia survive well during summer months, even at water temperatures exceeding 37°C, winter water temperatures of 14 to 18°C, result in reduced tilapia growth and mortality. For this reason, a number of alternative filter-feeding organisms were studied including (in California) the Sacramento blackfish, *Orthodon microlepidotus* (a native California cyprinid), Chinese bighead carp, and a hybrid of common carp and goldfish, *Cyprinus carpio* × *Carassius auratus*. In South Carolina, freshwater mussels and other bivalves were also found to be capable of removing algal cells efficiently. Tilapia coculture was demonstrated to be effective at stabilizing field algal cultures by reducing zooplankton densities and occurrence. Furthermore, tilapia populations were successful in controlling algal standing crop, providing a method to maintain optimal Secchi disk visibilities of 15 to 18 cm. Both tilapia and shellfish populations were demonstrated to be effective in controlling the dominant algal genera in the ponds. Tilapia effectively eliminated algal population dominance by cyanobacteria and associated off-flavor of fish flesh. Tilapia populations were demonstrated to feed more efficiently on cyanobacteria (Turker *et al.* 2002, 2003a–d). Alternatively, shellfish selectively remove green algae, driving the pond algal populations toward cyanobacteria dominance (Stuart *et al.* 2001). In 1998 and in 1999 late-season reductions in catfish off-flavor was observed as 2-acre units were seen to shift from early cyanobacterial dominance to green algae as initial stockings of 100 tilapia breeding-pairs/acres expanded in number and weight as the season progressed.

An additional important function of tilapia grazing in the PAS is to provide a cost-effective technique to maintain young algal cell ages. Maintaining 10 to 25% of cultured fish biomass (channel catfish) as tilapia biomass was seen to reduce average algal cell age from 6 to 10 days to 2 to 3 days (fig. 13.6). The younger rapidly growing algal community yields more net oxygen production at reduced levels of pond respiration, and is less prone to culture instability.

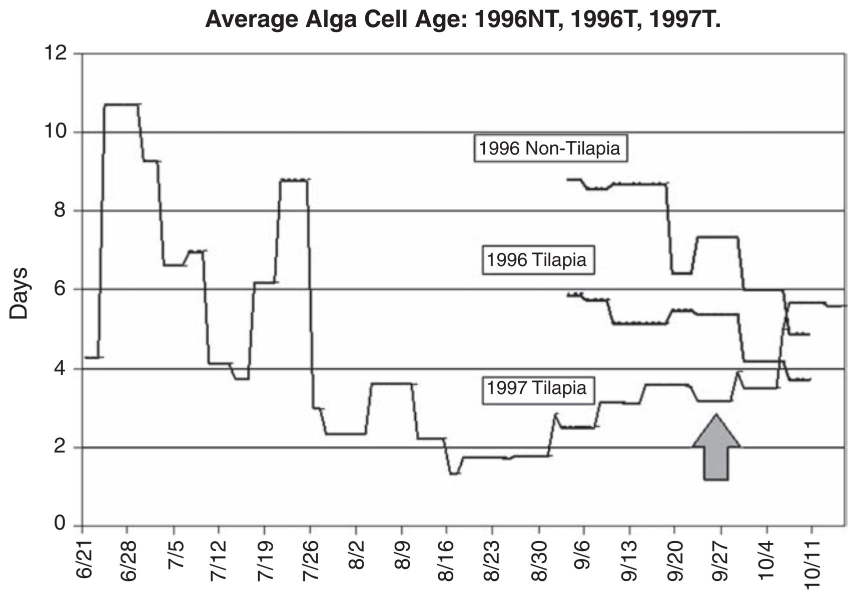


Figure 13.6 Algal cell age reduced with tilapia filtration.

13.1.6 PAS algal harvest

After four years of catfish culture, the data suggested that a significant portion of the algal growth capacity of the PAS was being wasted. Light/dark-bottle determinations of algal photosynthesis revealed that PAS algal production was incorporating nitrogen at rates 2 to 3 times greater than the amount added from fish-feed (table 13.2). In addition, system and sediment oxygen demand was progressively increasing. In the early PAS design, significant quantities of algal biomass were observed to settle in the system at large. If system design does not provide for removal of excess algal production, the biomass settles to bottom and decays, recycling soluble nitrogen and phosphorus back into the water column. At carbon fixation rates of 10 g-C/m^2-d corresponding to 1.8 gm N/m^2-d, calculations indicate that PAS feed assimilation capacity should

Table 13.2 PAS algal nitrogen uptake vs. nitrogen added to system from fish respiration.

Feed Rate kg/ha-d	System	Net Photosynthesis mg O_2/L-day	Respiration mg O_2/L-day	Nitrogen Addition mg-N/L-day	N-uptake/ N-addition
90	Typical Pond	10	5–8	—	
100	1996 PAS	31	13	0.80	2.2
200	1997 PAS	60	14	1.40	2.4
100	1998 PAS	70	24 ?	1.40	2.8
225	1999 PAS	90	24 ?	1.60	3.2

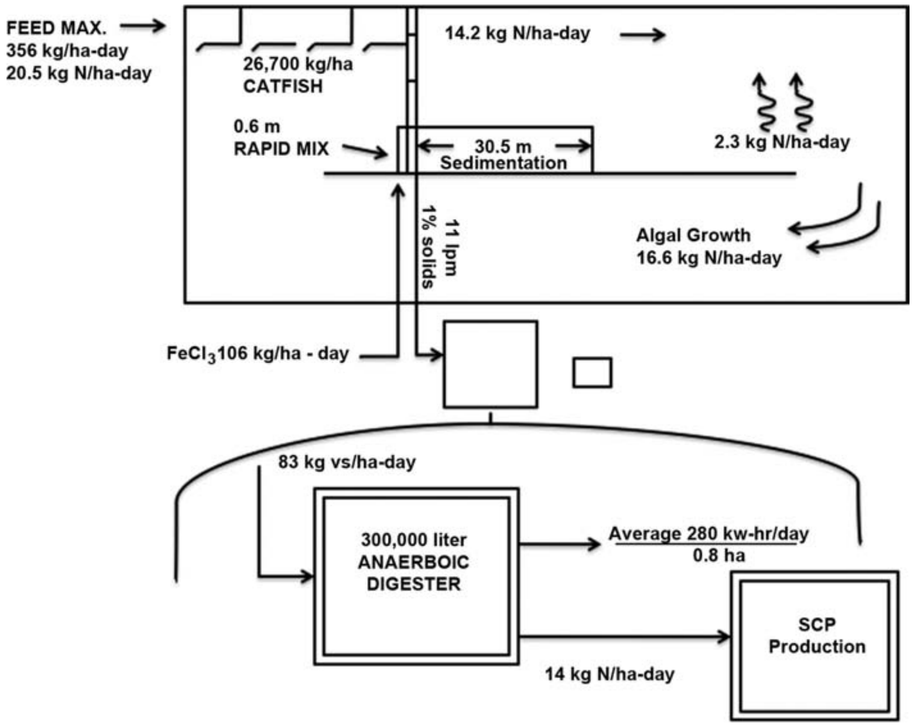


Figure 13.7 Predicted feed assimilation and fish yields with algal harvest.

be in excess of 450 kg/ha (400 lb/ac/d) suggesting potential catfish yields of 33,700 kg/ha (30,000 lb/ac). This indicated that PAS production capacity could likely be expanded (beyond that demonstrated) if nitrogen recycling from pond sediments could be reduced (fig. 13.7). This led to the conclusion that a system was needed to harvest and remove algal biomass from the pond.

The primary limitation standing in the way of widespread use of high-rate algal ponds for biomass production and water treatment is lack of cost-effective methods for harvest, removal, and concentration of algal biomass from ponds. Efficient algal harvest is also the critical cost-limiting step in production of algae for feedstuffs and chemicals. There have been many attempts to develop technology for harvest of single-celled algae from water, mostly based on filtration, centrifugation, or algal settling. Unfortunately, most of these technologies have proved to be inefficient and/or very expensive and, as such, are limited to commercial production of higher-value products (such as pharmaceuticals). Attempts have been made to use iron and aluminum salts to flocculate and settle algae onto a slow moving dewatering belt for removal from the PAS. Although the salts and belt worked well, the chemical costs were prohibitive. However, it was discovered that tilapia holding-cells could be placed over the belts, and the fish would enhance algal bio-sedimentation. This approach proved successful and cost effective in both South Carolina and California. The process is based

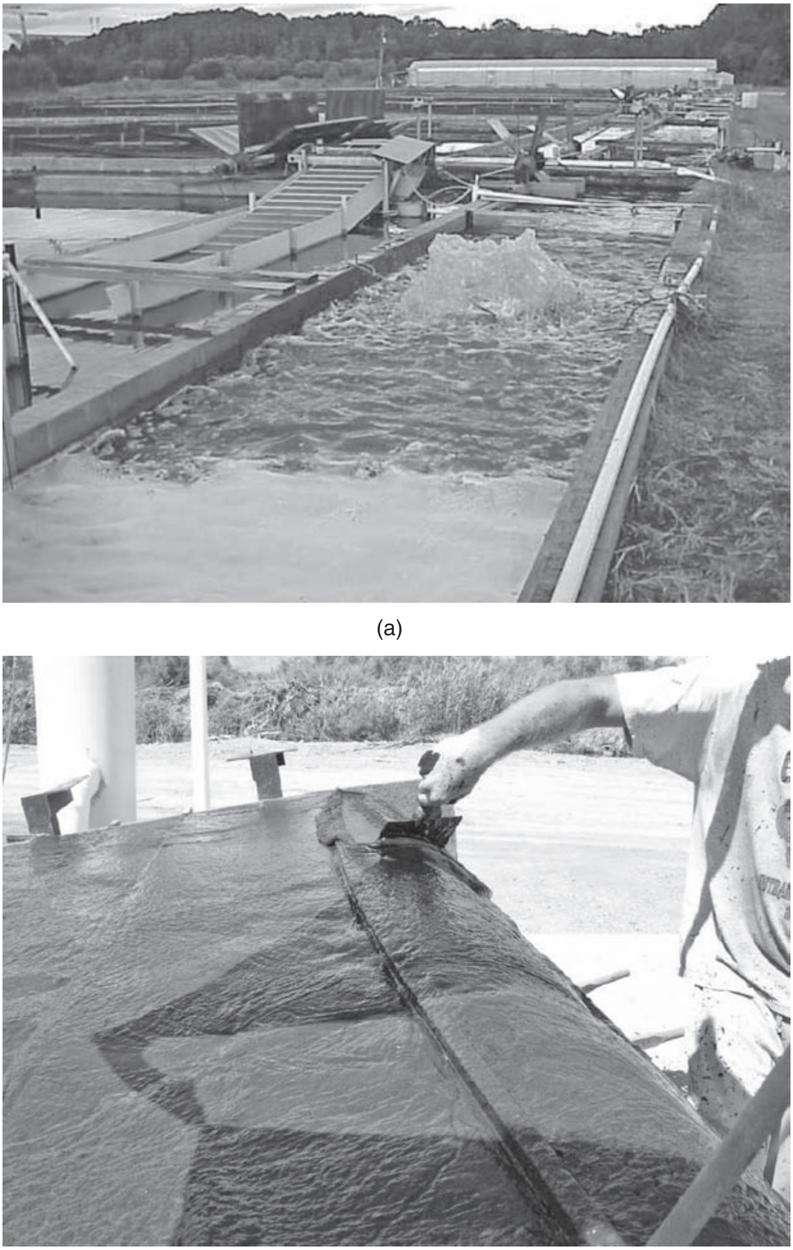
on the fact that a fraction of the algae consumed by tilapia is converted into fish biomass, but the greater part passes through the fish to be excreted as fecal matter. The algal biomass is now bound into packets that settle rapidly onto the belt. The conveyor belt advances continuously at a critical angle, lifting the thickened algal sludge from the water column (fig. 13.8). Field trials showed that 90 to 95% of algal biomass production might be harvested using tilapia. The harvested algal biomass can be fermented to yield methane gas, which may be used as an energy source reducing dependency of fish production on fossil fuels, or processed into feed for secondary fish production, potentially providing aquaculture protein self-sufficiency.

13.1.7 Reduced environmental impact and water use in the PAS

In typical pond aquaculture, only about 25% of the feed-nitrogen and feed-carbon is incorporated into fish biomass. The remainder of the nitrogen and carbon supplied to the pond is lost through volatilization to the atmosphere, denitrification, methane fermentations, seepage, or water discharges—all of which can result in nutrient enrichment of surface and/or ground waters, and atmospheric enrichment with volatile ammonia and greenhouse gases. The PAS technology allows for improving feed utilization efficiency (in raceway culture), thereby eliminating feed wastage, which results in reductions in atmospheric emissions, water pollutants, and other environmental impacts associated with fish production. The energy requirements of PAS are substantially reduced as a result of reduced aeration requirements due to separation of the algal and fish production processes and increased O_2 production in the algal channels. Paddlewheel mixing is more energy efficient than airlift or centrifugal pumps, moving large volumes of water at low head (Benemann & Weisman 1993; Brune 1997; Oswald 1995). The lower costs, combined with higher productivity, are key factors encouraging widespread PAS implementation enabling industry wide reductions in aquaculture environmental impacts. The shallow depth of the PAS system 0.5 to 0.6 m (1.5 to 2.0 ft) as opposed to 1.5 m (5 to 6 ft) for conventional ponds requires an initial filling of only 25 to 30% of water volume as compared to conventional pond-based catfish production.

13.1.8 PAS economics

A detailed economic analysis of the PAS was prepared by Goode *et al.* in 2002. In his analysis, 18.2 ha (45 ac) and 73 ha (180 ac) of PAS units producing 413,000 kg and 1,716,000 kg (909,800 and 3,775,670 lb, respectively) of catfish were compared to 65 and 260 ha (160 and 640 ac) of conventional ponds producing 318,000 and 1,293180 kg (700,000 and 2,845,000 lb) of catfish. Goode's analysis suggested that PAS culture could reduce production cost by UD$0.06 to 0.09/kg ($0.13 to 0.19/lb). However this projection was dependent



(a)

(b)

Figure 13.8 Algal sedimentation belts at Clemson (a) and concentrated algal biomass from belt in California (b).

upon successful carryover and growout of the overwintered fish (approximately 20% of the total system harvest). In 1999, PAS growth trails proliferative gill disease produced significant mortality in winter carryover fish. This source of loss (unless controlled) would result in the comparable PAS production costs ranging from US$0.009 to 0.023/kg ($0.02 to 0.05/lb) higher than conventional production costs.

Extending the analysis conducted by Goode *et al.* (2002) to commercial catfish farming is confronted with additional limitations. To date, only the Alabama modification of the PAS (described further on) has been used in a commercial catfish production—and only on a limited scale. Both the Clemson PAS and the Mississippi modification (the "split-pond") have been used under controlled, experimental conditions where catfish populations are predominately stocked in the spring, grown throughout the summer, and harvested in the autumn. While this approach can provide estimates of maximum production and allows optimization of system operation, constraints encountered under commercial conditions will likely reduce production and profitability.

Traditional pond catfish culture constraints include algae-generated fish off-flavor, loss of fish to predators, infectious diseases, and reduction in production potential related to fluctuating demand for fish by processing plants. Incidence of algae-related off-flavor is significantly reduced in the Clemson PAS because of effects of plankton grazing by tilapia cocultured with catfish. Insufficient information exists on the incidence of off-flavors in the Alabama and Mississippi PAS modifications, although it is clear that algal off-flavor is not eliminated in the Mississippi split-pond, which currently does not include tilapia coculture and algal grazing. Loss of fish to predation, particularly avian predators, is reduced to insignificance in all PAS modifications because predation control under fish confinement is relatively inexpensive and simple to implement. However, PAS modifications operated under commercial conditions will face uncertain risks from continuous operation and infectious diseases, and these risks interact significantly.

Catfish processors require fish year-round and some food-sized fish must be stored in ponds through the winter and spring to meet this demand. In effect, pond space that could be used to produce a new crop is used (indirectly) by the processors to hold fully grown fish in inventory. The impact of year-round demand for food-sized fish can be minimized, but not eliminated, by staggering production start dates in different ponds so that multiple populations reach market-size at different times throughout the year. This requires considerable management skill and access to fingerlings of desired sizes for stocking throughout the year, which is currently difficult for the catfish industry. Even if production is staggered so that food-sized fish are available throughout the year, some fish will need to be held in inventory to meet processor demands for fish in winter and spring, because low water temperature limits winter catfish growth in the southeastern United States. Overwintering food-sized catfish to meet winter and early spring processor demand exposes fish to increased risk of infectious disease.

There is no evidence of increased catfish loss to bacterial diseases in any of the PAS modifications. On the contrary, if/when bacterial disease occur, they are easier to manage than in traditional ponds because diseased fish are identified earlier and medicated feed can be delivered more effectively to confined fish. However, there is one common disease of channel catfish that appears to be a significant risk in some modifications of the PAS. Proliferative gill disease (PGD) is a serious disease of channel catfish in traditional earthen ponds. The disease led to loss of fish in both the Clemson PAS and the Mississippi split-pond PAS modification. The disease is caused by the myxozoan parasite *Henneguya ictaluri,* which infects the gills of channel catfish and its blue catfish hybrid, inducing severe hemorrhage of the gill filaments. Changes in gill structure interfere with gas exchange, resulting in hypoxia. The common, sediment-dwelling oligochaete worm *Dero digitata* is the intermediate host for the parasite. In the southeastern United States, the disease occurs in spring and, less commonly, in autumn. Currently, there is no treatment for the disease.

Outbreaks of PGD are not uncommon in PAS modifications, which may be related to the environment provided in the PAS for the oligochaete intermediate host. The worm probably proliferates in the "waste-treatment" side of the system where organic-enriched sediments from algal sedimentation and fish wastes provide food to the benthic invertebrates serving as intermediate host. Because the disease incidence peaks in spring, there is significant interaction between PGD risk and need to overwinter fish both for growout of undersized fish and holding of fish to meet springtime processor demands. These interacting risks could negatively impact economic returns in the PAS and PAS modifications. After the 1999 fish loss in the Clemson PAS, prophylactic lime treatment of PAS sediments was seen to substantially eliminate incidence of PGD is subsequent culture years. However, without automated systems to apply lime to ponds, labor requirements for manual lime application would be excessive.

13.2 PAS fingerling production

In an effort to reduce the need to overwinter catfish, research was directed at use of the PAS to produce larger sized fingerlings for stocking in PAS growout cages. In 2005, raceways in the 0.8 ha (2 ac) Clemson PAS unit were reconfigured into a series of nine, 1.83 m × 2.89 m × 1.22 m deep cinder-block cells. The cells were designed to allow for containment and culture of channel catfish fry to advanced fingerling sizes. The objective was to utilize the improved water treatment capacity and fish culture practices of the PAS to increase size and yield of catfish fingerlings within a single season.

At the Clemson facility, catfish eggs were harvested from broodfish ponds during the second and third weeks of May, after which they were hatched in tanks held at a constant a water temperature of 80°F. Once hatched, the fry were moved into 0.3 cm (1/8 inch) mesh-size rearing containers, and later to 0.44 cm (3/16 inch) mesh nets, then finally into 0.58 cm (1/4 inch) mesh net-pens where they remained until harvest. Each container or net-pen was

Figure 13.9 Continuous application of water and feed to fingerlings held in PAS net-pens.

supplied with water flow delivered with a combination of airlift pumps and submerged aerators (fig. 13.9). At initial stocking the fish were fed a starter feed of 52 to 56% protein, supplied by automated feeders. The fingerlings were harvested after 143 days of culture, yielding an average fingerling weight of 100 to 120 g/fingerling (fig. 13.10). Maximum feed application rates exceeded 135 kg/ha-d of 40% protein feed at a maximum fingerling carrying capacity of 4,200 kg/ha. Fingerling feed uptake rates were pooled from three seasons (2005, 2006, and 2007) yielding a feed application relationship of:

$$\text{Feed rate as percent of body weight per day} = 0.3233(\text{fish weight in grams})^{0.551} \tag{2}$$

In 2008, the PAS fingerling growth cells were configured to allow for passive water flow addition to each cell by utilizing the raceway paddlewheel, as opposed to using airlifts or aerators to provide water as was done in the 2005 to 2007 seasons. The intent was to investigate the possibility of using lowering system installation and operational costs. The best configuration, providing controllable high-flow rates through the cells, consisted of combinations of baffles in the water delivery channel and "angled flaps" in the individual bins and net-pens directing water flow into circular paths within the fingerling cells. Water flow rates averaged 1,514 Lpm (400 gpm) in the bins (as opposed to 151 Lpm using

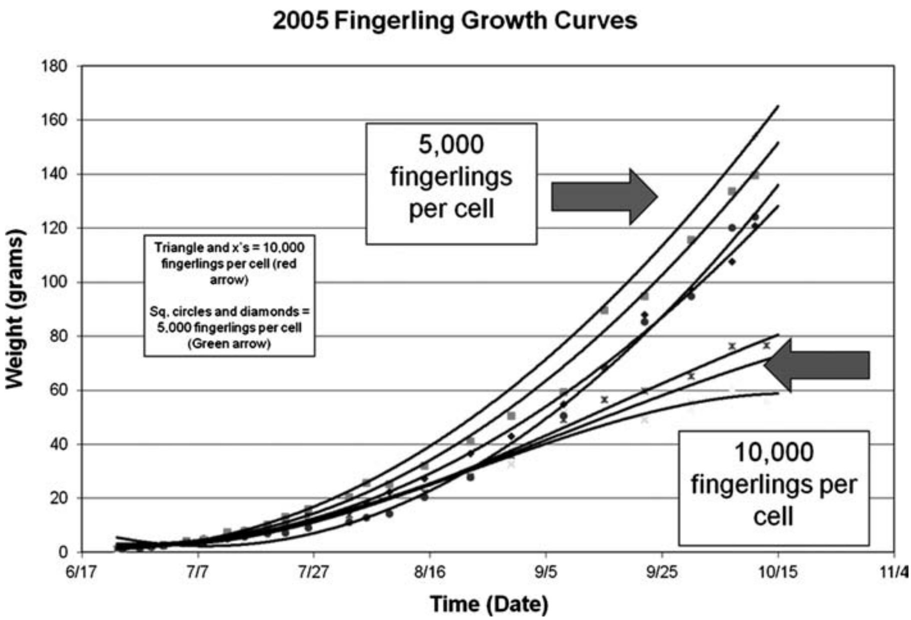


Figure 13.10 Accelerated fingerling growth compared to conventional pond fingerling growth.

airlifts) and 7,570 Lpm (2,000 gpm) in net-pens (as opposed to 1,362 Lpm with aerators). Bin and net-pen hydraulic detention times were reduced to 0.4 to 0.85 minutes using passive flow as opposed to "pumped-flow" detention times of 2 to 5 minutes.

Overall, average fry/fingerling growth rates and yields observed in the 2008 PAS configuration were statistically the same as fingerling growth observed in earlier trials. The experimental trials suggested catfish fingerling growth could be significantly intensified and accelerated in the PAS. Fingerling production trials in the PAS demonstrated that catfish fingerlings in excess of 100 gm size could be produced in a single 140-day season at fingerling densities of 12,350 fish/ha (5,000 to 6,000 fish/acre). Fingerlings of this size may be grown to market-sized 0.68 kg (1.5 lb) fish in a single growout season, potentially reducing the amount of fish biomass that must be overwintered

13.3 Flow-through PAS: the controlled eutrophication process

13.3.1 Eutrophication of the Salton Sea in Southern California

The Salton Sea (SS) is a large inland lake of 945 km^2 (365 square miles) 69 m (227 feet) below sea level, with no outlet, which has been accumulating salt and nutrients from municipal storm water, treated sewage, industrial waste discharges, and agricultural drainage for nearly 100 years. Over geologic time, the Salton Basin and Lake Cahuilla were periodically flooded due to natural diversions of the Colorado River. After each diversion ceased, the area reverted

to a dry lake bed. As the region became populated and large-scale irrigation drainage and municipal and industrial waste-streams from the United States and Mexico were dumped into the basin, the SS became a permanent water body, with evaporative losses equaling tributary inflows. Buildup of salts and nutrients from Imperial Valley and Coachella Valley discharges led to the development of an inland hypereutrophic, hypersaline lake. As the SS increased in salt content, it became a stage for a succession of ecosystems ranging from freshwater to brackishwater and ultimately to only the most salt-tolerant organisms. A variety of solutions have been proposed to improve water quality in the SS, ranging from evaporative ponds to concentrate salts to pumping of water for discharge to the Gulf of California. However, reducing the salinity will not resolve the more serious water quality problem associated with high-nutrient loads driving the extreme eutrophication. Large-scale algal blooms, followed by senescence of these blooms, lead to catastrophic low-dissolved oxygen, triggering massive fish mortalities resulting in widespread odor problems. A cost-effective solution to this problem is required.

Recently, the establishment of freshwater impoundment zones within the SS perimeter near the major freshwater river inflows has been proposed. As the SS continues to evolve to a hypersaline environment inhospitable to most freshwater and brackish organisms, this freshwater zone would continue to support fish and the fish-eating birds. Whether the freshwater impoundment zone is implemented or not, lowering the amount of nutrients flowing into the sea is of paramount importance in maintaining acceptable water quality (Setmire *et al.* 1993). The principal tributaries to the SS (the Alamo, New, and Whitewater Rivers) contain 0.5 to 2.00 mg/L of total phosphorus at N:P ratios of 4.6 to 39.6 (Setmire 2000). Phosphorus is considered to be the limiting nutrient in the SS.

13.3.2 PAS aquaculture for eutrophication control

Kent SeaTech Corporation and Clemson University conducted research, developments, and demonstrations involving the application of the PAS for concentrating and removing nutrients from wastewater streams. A modified version of the PAS described as the controlled eutrophication process (CEP), utilizes dense populations of single-celled algae cultivated in high-rate algal ponds and harvested using tilapia driven bio-sedimentation originally developed for aquaculture applications (Brune *et al.* 2007). The CEP relies upon the water treatment function of the PAS. Kent SeaTech and Clemson demonstrated technical and economic feasibility of using CEP technology to reduce nutrient concentrations in aquaculture and wastewater effluent to essentially zero.

The typical PAS installation for aquaculture effluent treatment and reuse has an intensive primary fish production zone in which high-value fish species such as channel catfish or striped bass are cultured. In some applications, a detritivore fish species is placed downstream from the primary fish production zone to consume uneaten food, fecal matter, and particulate waste. Downstream from this area, the treatment zone consists of paddlewheel-mixed high-rate algal growth basins where waste nutrients from the primary fish species are converted

into algal biomass. After the treatment zone, a secondary fish-zone houses a filter-feeding fish that consumes algal cells converting a portion into fish biomass. The remaining algal biomass is excreted onto the algal concentration belt for removal from the system.

13.3.3 PAS/CEP for remediation of the Salton Sea

For remediation work, CEP units are configured differently from the PAS used for aquaculture water reuse. In the aquaculture system, no water is discharged to the environment and filter-feeding fish are held in the algal growth basin, resulting in equilibrium algal cell concentrations typically not exceeding 50 to 60 mg/L VS. However, in the CEP application, water flow through the system provides hydraulic retention times of 3 to 4 days. Under these conditions the algal standing crop is typically maintained at densities of 80 to 160 mg/L VS. In aquaculture applications, the PAS process allows the production of fish with minimal impact on the environment.

CEP treatment at the SS operates as a flow-through process treating nutrient-enriched water from agriculture drainage to the Whitewater, New, and Alamo Rivers—the three principal tributaries of the SS. The major components include (1) the nutrient-enriched water, (2) the high-rate pond with paddlewheels, and (3) the algal harvest zone (fig. 13.11). The nutrient-laden water is brought into

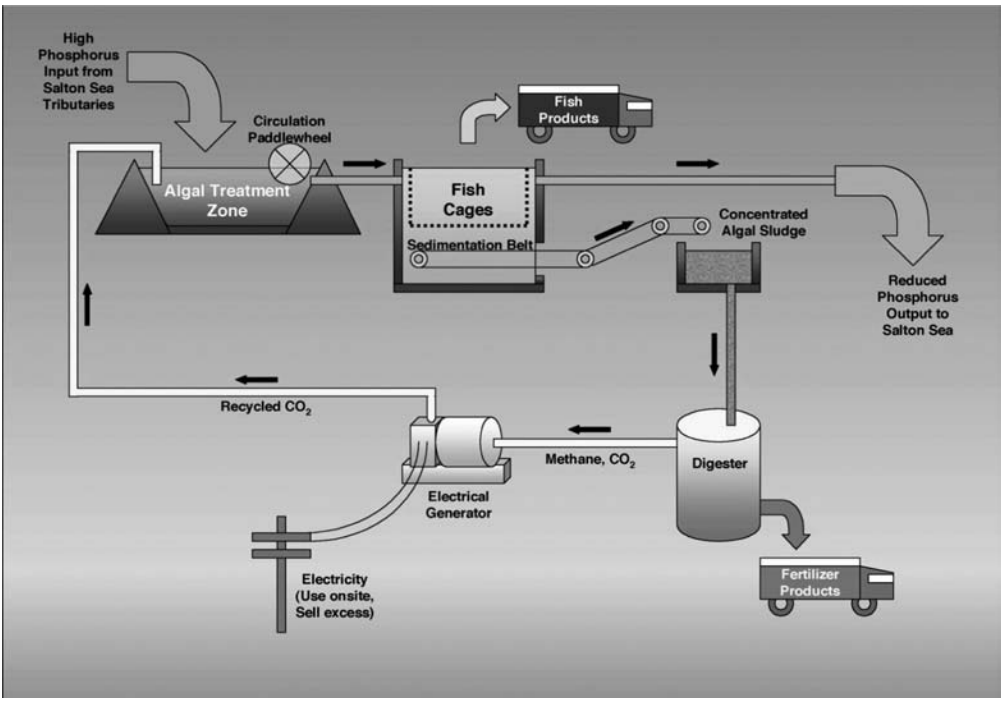


Figure 13.11 The PAS/CEP for waste nutrient control using fish harvest of algal biomass.

Figure 13.12 Solar-drying of CEP produced algal biomass.

the algal treatment zone where paddlewheels continuously mix the water column. Stable algal populations grow at an accelerated rate converting nutrients to algal biomass. The algae-laden water from the treatment zone is passed through high densities of confined tilapia (or other filter-feeder fish) and across an algal sedimentation zone or belt, producing steady-state algal cell density of less than 10 to 15 mg/L. As much as 75 to 90% of the algae-bound N and P can be removed without the need for chemical flocculants. After the algal biomass is harvested, separated, and removed from the water column it can be solar dried (fig. 13.12), and the treated water may be returned to the river for discharge to the sea.

13.4 Photoautotrophic and chemoautotrophic PAS for marine shrimp production

Because of actual and perceived negative environmental impacts of marine shrimp production Clemson efforts where directed (in 2002) to applications of the PAS design in support of marine shrimp production. Four 250 m^2 (0.0625 ac) greenhouse-covered PAS units were designed, installed, and operated at Clemson for marine shrimp (*Litpenaeus vannamei*) production trials.

Initially, in 2003, feed application rates of 280 kg/ha-d were maintained resulting in a final shrimp yield of 16,800 kg/ha. In 2004, feed application rates were pushed to 787 kg/ha-d with a shrimp yield of 25,600 kg/ha. In 2005, feed application rates peaked at 1,662 kg/ha-d with a shrimp yield of 37,339 kg/ha (33,232 lb/ac). In 2003, net photosynthesis in the marine units ranged from 0 to

19 g-C/m^2-d with an average of 4.2 g-C/m^2-d. In 2004, algal fixation declined to 0 to 15 g-C/m^2-d at an average of 3.7 g-C/m^2-d. In 2005, photosynthesis further declined to 0 to 6 g-C/m^2-d at an average of 1.1 g-C/m^2-d at average feed rate of 683 kg/ha-d (608 lb/ac-d).

In contrast, the six 0.13 ha (1/3 ac) freshwater PAS units yielded catfish production approaching 22,000 kg/ha (19,860 lb/ac). Feed application rates to the catfish units ranged between 163 kg/ha-d (145 lb/ac-d) and a maximum of 286 kg/ha-d (255 lb/ac-d). Net photosynthesis in these units ranged from 10 to 120 mg O_2/l-d (1.9 to 22.5 g-C/m^2-d).

The decline in photosynthesis in the marine units at the high feed rates was dramatic and very obvious. While peak photosynthetic rates as high as 22.5 g-C/m^2-d were observed in the outdoor catfish units, long-term sustained maximum rates of 10 to 12 g-C/m^2-d were more typical. However, the shrimp units typically yielded maximum sustained peak photosynthetic rates much lower than 10 g-C/m^2-d. By the time external organic carbon addition had reached 6.0 g-C/m^2-d, algal carbon fixation declined 5 g-C/m^2-d. At 10 g-C/m^2-d external carbon application, algal fixation dropped to 3 g-C/m^2-d. And when the system was receiving 50 g(organic)-C/m^2-d of external carbon (corresponding to 3.5 times the rate of catfish PAS feed-rate), photosynthesis was essentially zero. As a result, the shrimp water column was populated by 200 to 500 mg/L of nitrifying bacterial flocs, which became the dominant nitrogen control mechanism. Shrimp production in excess of 28,000 kg/ha (25,000 lb/ac) is possible using non-photosynthetic systems (table 13.3). However, aeration and mixing energy requirements were seen to increase substantially from 7.7 to 9.2 KW/ha (4 to 5 hp/ac) in an algal-dominated system to an excess of 115 KW/ha (60 hp/ac) within a bacterially dominated system.

Field studies suggest that decline in algal productivity as a result of increased organic loading is likely the result of algal light-limitation arising from heterotrophic and chemoautotrophic bacterial biomass within the water column. This effect is exaggerated in shrimp units where fecal solids and uneaten food

Table 13.3 Field observed and projected algal photosynthetic limits vs. feed loading rate in shrimp PAS production units.

Feed Rate kg/ha-day	Production[1] kg/ha	Nitrogen Loading[2]		Photosynthesis[3]	
		gm-N/m^2	mg-N/L	g-C/m^2-d	mg-O_2/L
112	4,210/5614	0.5	0.9	2.6	14.1
224	8,420/11,227	0.9	1.9	5.3	28.2
560	21,050/28,070	2.4	4.7	13.4	70.3
1,120	42,100/56,135	4.7	9.4	26.7	140.6[4]
1,684	63,150/112,270	7.1	14.1	40.0	210.9[4]

[1] Growing season = 120 days (catfish) or 200 days (shrimp); CF = 2/1; average feed = 50% of peak feed rate.
[2] 35% protein, 75% N-release to water, water column = 0.5 meter deep.
[3] Algal C/N = 5.6/1, C/O_2 = 1/1 molar.
[4] Photosynthetic rate required to match nitrogen loading rate; these rates are not observed in practice.

add to the accumulation in the water column. Aggressive solids management, using a combination of settling and aeration basins, coupled to tilapia polishing basins may be used to reduce this light limitation. Advantages of maintaining enhanced algal production at high organic load within the PAS include reduced system oxygen demand, reduced aeration and mixing energy requirements, reduced alkalinity destruction/consumption, and improved pH management—all leading to increased feed application and fish/shrimp carrying capacity.

13.5 Alabama in-pond raceway system

Work in west Alabama (supported by Alabama Cooperative Extension Service, Alabama Experiment Station, and the Alabama Catfish Producers Association) has focused on development and demonstration of an "in-pond raceway" fish production system applying technologies and management approaches to utilize existing earthen ponds to increase production yield and efficiency (fig. 13.13). Fish production costs on most southern catfish farms currently exceed US\$1.65/kg (\$0.75/lb). The objective of this research was to develop and demonstrate in-pond systems, strategies, and technologies providing improvements supporting sustainable and profitable US aquaculture enterprises.

Commercial scale in-pond raceways were installed and operated on farms in west Alabama in 2007 to 2008. The design represents a rearrangement of partitioned aquaculture systems (PAS) pioneered by Clemson University that employ confined fish production using filter-feeding fish to harvest manure waste

Figure 13.13 Alabama in-pond raceway system.

and excess algae productivity. The Alabama system was installed in a 2.4 ha (6 ac) earthen pond of average depth of 1.7 m (5.5 ft). Six fish-production cells 4.9 m (16 ft) wide and 11.6 m (38 ft) long were constructed from concrete blocks on a reinforced concrete pad (fig. 13.13). The cells were arranged side by side sharing common walls. Each cell was equipped with a 0.38 KW (0.5 hp) water-mover (paddlewheel) at the upstream end rotating at 0.7 to 1.5 RPM, providing a raceway water exchange every 1 to 2 minutes. For additional life support, an aeration grid was installed downstream from the water-mover. It was supplied with low-pressure air from a 1.1 KW (1.5 hp) Sweetwater blower. Fish were confined in cells using two PVC coated steel mesh panels extending across the width of each cell, one placed upstream adjacent to the aeration grid and the second was placed downstream 2.4 m (8 ft) from the end of the raceway. An automatic, timer-controlled feeding system was installed in each cell and was supplied with bulk feed via an overhead tube originating at a bulk-feed storage tank.

At the discharge of the raceway cell a V-shaped manure pit was installed at a "quiescent zone," designed to allow settling of waste or other particles as they passed from the cells. The V- shaped trap extends across width of the raceway. A baffle was installed on the long axis of the pond forcing water discharging from the production cells to circulate around the open-pond, preventing short-circuiting to the intake channel.

A different version of the in-pond system was installed at a farm in Greene County, Alabama. This system consisted of two floating cells of dimensions similar to the fixed system described previously (fig. 13.14). The main difference

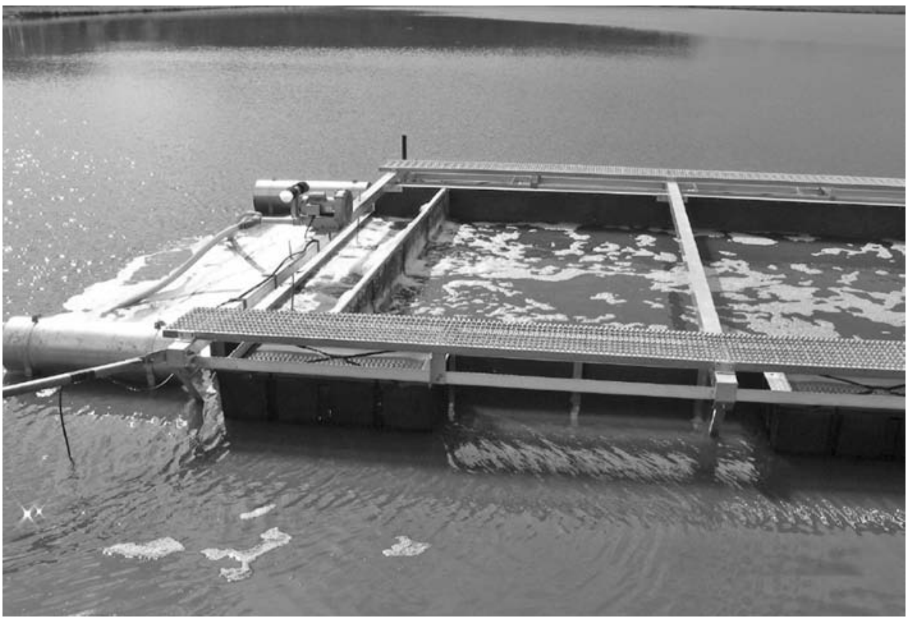


Figure 13.14 Floating raceways.

is that the water is moved through the floating raceway by an airlift pump attached directly to the inlet to each cell. The airlift was used to aerate, pump, and mix the inlet water. The airlift devices were powered by 1.1 KW (1.5 hp) Sweetwater blowers. Water exchange rates were adjusted to be the same as in the paddlewheel driven fixed-cell system.

In the fixed-cell systems, the units were stocked with 9,000 to 10,000 juveniles averaging 80 to 200 grams in weight. Dissolved oxygen levels remained satisfactory and stable (>1.5 mg/L and <15.0 mg/L) in all cells. Ammonia and nitrite levels remained well below stressful levels. Results during 2008 have demonstrated mean catfish survival of 91 to 95% with one cell at 80%. Feed conversion efficiency (FCR) averaged 1.3:1 (ranging from 1.1:1 to 1.6:1) at a production average of 28,000 kg/ha (25,000 pounds/ac).

Aeration energy use was reduced by approximately 50% compared to conventionally aerated catfish production ponds in the area. In both configurations, observations suggest the in-pond production strategy significantly and reliably increased fish yield/acre to 33,700 kg/ha (30,000 lb/ac) at survival rates >90% and at feed efficiencies routinely below 1.5:1. A fish production management guide and economic model is currently under development. We anticipate that improvements in survivorship, feed efficiency, management of disease, and overall increased production will significantly reduce the cost of production, and substantially improve enterprise profitability.

13.6 Mississippi split-pond aquaculture system

A modification of the PAS has been constructed at Mississippi State University's National Warmwater Aquaculture Center that takes advantage of existing pond infrastructure in the major catfish-growing area of the southern United States. These systems are referred to as "split-ponds" to differentiate them from the PAS. Split-ponds are constructed by retrofitting existing earthen ponds, as opposed to a complete redesign as is done with construction of the PAS. As originally conceived, the goal of the split-pond was to take advantage of the fish-confinement benefits of the PAS, such as facilitation of feeding, inventory, harvest, health management, and protection from predators. During development of the system, it became evident that loading rates and fish production were significantly greater in the split-pond than in traditional ponds. The split-pond thus represents an intermediate level of intensification between traditional earthen ponds and the PAS.

The split-pond has a relatively smaller algal basin (about 70 to 80% of the total area) and a larger fish-holding area than the PAS. Fish are held at only 5 to 10 times the density of traditional ponds. The split-pond is constructed by dividing an existing earthen pond into two unequal sections with an earthen levee. The levee is then breached with two sluiceways. One sluiceway is fitted with a large, slow-turning paddlewheel (fig. 13.15), which moves water out of the fish-confinement area. The second sluiceway provides return flow from the algal basin into the fish-confinement area (fig. 13.16). Metal screens are installed

Figure 13.15 Paddlewheel at Mississippi split-pond levee.

Figure 13.16 Return-flow sluiceway.

in each sluiceway to prevent fish escape. Aerators in the fish-confinement area provide supplemental dissolved oxygen supply at night. The system is currently operated as a catfish monoculture, although it is easily adapted to coculture with tilapia or other fish.

The key design parameters for the split-pond are water flow rate and aerator capacity. During daylight hours, water flowing from the algal basin provides oxygen for fish in the confinement area. The required flow rate is calculated from estimates of the oxygen consumption rate of the confined fish at the highest expected biomass loading and most extreme water temperature. The paddlewheel size required to supply the desired flow rate is determined empirically. At night, dissolved oxygen cannot be supplied by photosynthesis in the algal basin, so the large paddlewheel is turned off to stop water exchange between the two sections. At this time dissolved oxygen is provided by mechanical aeration within the fish confinement zone. Aeration requirements are predicted by matching aerator oxygen transfer rate to maximum projected fish oxygen consumption rate. Water exchange and mechanical aeration never occur at the same time in the split-pond.

As an example, a 2-ha earthen pond at Mississippi State University was reconfigured into a 1.42-ha algal basin and 0.40-ha fish-confinement area. Based on previous studies in prototype split-pond units, the 1.82-ha system was designed to hold a maximum fish biomass of 40,000 kg, all of which were contained in the 0.40-ha confinement area. Required water flow from the algal basin was estimated at 50 m^3/minute at an inflow dissolved oxygen concentration of 5 mg/L. A six-blade 3.66-m-long, 2.4-m-diameter paddlewheel operated at 2.5 rpm at a wetted paddlewheel depth of 1.1 m, producing a water flow of 60 m^3/minute, more than adequate to supplying sufficient oxygen supply to fish during daylight hours. Nightly aeration in the fish confinement area was provided by two 7.5-kW paddlewheel aerators.

After seven years of study, net annual catfish production in the split-pond ranged from 17,000 to nearly 20,000 kg/ha—2 to 4 times that achieved in traditional ponds and marginally less than in the PAS system. At stocking rates of 25,000 fish/ha, fish were grown from an initial weight of 50 to 70 g/fish to 0.80 to 0.90 kg/fish in a seven-month growing season. Feed conversion ratios (weight of feed fed divided by net fish weight gain) were approximately 1.8:1.

Although daily feeding rates exceeded 250 kg/ha for extended periods, total ammonia-nitrogen concentrations seldom exceeded 1 mg/L, except when phytoplankton communities crashed and in late autumn when cooler water temperatures lead to slower rates of nitrogen assimilation by the pond microbial community. When phytoplankton populations crash, rates of dissolved oxygen production and nitrogen assimilation in the algal basin decline markedly and water exchange between the algal basin and the fish-confinement area becomes a liability rather than an asset. During those periods, which have occurred at a frequency of less than once per year, water exchange is stopped and the fish confinement area is aerated for a few days until the phytoplankton community recovers. The system is then returned to normal operation.

Although the split-pond may not achieve the fish production levels obtained in the PAS, it offers several advantages over traditional ponds. Aerating the small fish-confinement area is more effective at maintaining adequate levels of dissolved oxygen than in traditional ponds. Fish in the confinement area also are easier to feed and harvest. These attributes, combined with greater fish production, render the split-pond an attractive alternative for commercial catfish culture.

13.7 California pondway system

From 1983 to 2009, the Kent SeaTech (KST) fish production facility located in the agriculturally productive Coachella Valley of southern California was used for culture of hybrid bass, tilapia (*T. mossambica*), channel catfish (*Ictalurus punctatus*), and hybrid carp (*Cyprinus carpio* × *Carassius auratus*). This desert region provides very warm summers and mild winters that offer a farmer-friendly environment with high-quality geothermal groundwater aquifers supporting striped bass production, and 7.5 to 8.5 months of open-pond growing season.

During this time, KST conducted research on the use of algal-based systems for fish production and cost-effective wastewater treatment; the majority of this work was done in cooperation with Clemson University in South Carolina. In 2005, KST designed, installed, and operated commercial algae-based fish production systems utilizing Clemson's partitioned aquaculture system (PAS) concept and KST's pondway design.

Fifteen existing earthen ponds, originally used for the production of hybrid striped bass fingerlings, were modified into a single Kent SeaTech pondway/PAS system. The individual ponds were combined into a single pondway unit by removing sections of levees separating the ponds (fig. 13.17), allowing water flow between the ponds that was powered by two 7.5 hp steel paddlewheels, 3 m (10 ft) in diameter and 6 m (20 ft) long (fig. 13.18). The paddlewheels provided 113,000 to 151,000 Lpm (30,000 to 44,000 gpm) water flow through the pond's 2,600 m (8500 ft) lineal distance at a total head loss of 6.3 to 7.6 cm (2.5 to 3 inches). Total volume of the recirculating ponds at 0.9 m (3 ft) depth (area of 9.6 ha or 24 acres) was 89 million liters (23.5 million gallons) with an average water velocity of 0.05 to 0.07 m/sec (0.18 to 0.26 ft/sec).

Approximately 3,785 to 7,570 Lpm (1,000 to 2,000 gpm) of wastewater effluent from KST's striped bass production facility was fed continuously into the pondway after holding in two non-recirculating ponds. This water discharge averaged 3 mg/L ammonia, with a pH of 6.3 to 7.0, 20 to 40 mg/L of TSS (fish feces and uneaten feed), and at dissolved oxygen levels of 8 to 15 mg O_2/L. At 3,785 to 7,570 Lpm water addition, the pondway hydraulic retention time ranged between 8 and 16 days. Although the discharge water added ammonia and organic particulate load to the pondway system, the water addition acted indirectly as an algal harvest mechanism reducing algal cell age. Discharge water from the pondway system was sold to adjacent vegetable farms and seasonal

Figure 13.17 Overview of California pondway systems.

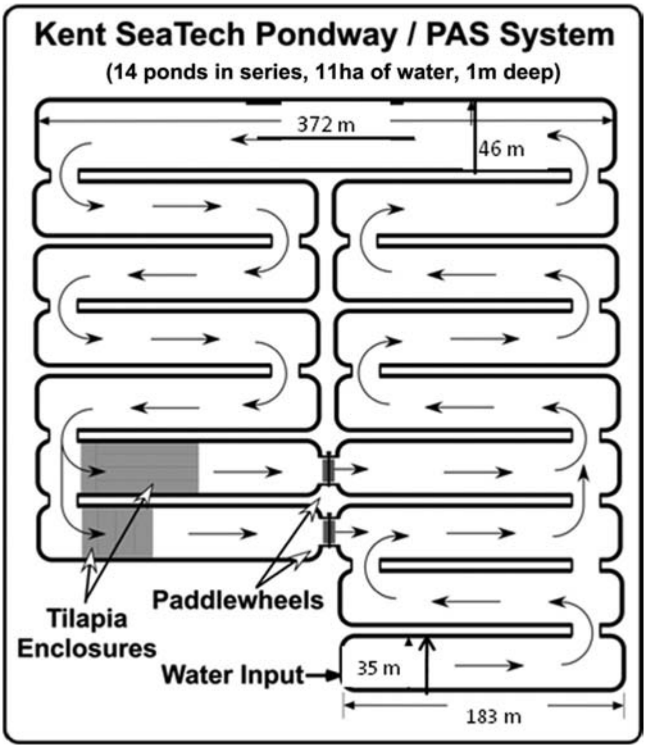


Figure 13.18 Schematic showing water flow in the California pondway system.

duck clubs. Excess water discharge beyond these needs was discharged to the Coachella Valley Stormwater Channel provided for by an NPDES discharge permit.

To limit construction costs, the original 0.9 m (3 ft) water depth of the preexisting ponds was maintained. The added water depth provided thermal buffering capacity against the extreme daytime water temperatures and hot air temperatures (38 to 50°C) of this Southern California region. During summer operations, the pondway water conditions ranged between a temperature of 25 to 38°C, with predawn dissolved oxygen concentration of 1 to 3 mg with afternoon concentrations of 10 to 22 mg O_2/L with a pH of 6.6 to 8.5, total ammonia-nitrogen concentration ranging from 0.3 to 3 mg/L (but usually below 1) and total suspended solids concentration ranging from 30 to 90 mg/L.

Two of the ponds were fitted with concrete floored and fenced fish enclosures. The first growout enclosure became operational in 2005, the second coming on line in 2007. The enclosures contained the production fish, both tilapia and carp/goldfish hybrids, partitioning them from the pondway algal growth basins. Water inflow to the fish production enclosures was split between two variable speed paddlewheels, which could be adjusted to independently control flow-rate across the two separate fish populations

The enclosures contained 1.5 KW (2.0 hp) high-speed paddlewheel aerators to supply nighttime aeration needs. In addition, each section contained a pure-oxygen diffuser hose or "aerotube" for emergency aeration needs. Each enclosure routinely held 22,700 kg (50,000 lb) of fish, with a maximum carrying capacity of 45,000 kg (100,000 lb) and 68,000 kg (150,000 lb), respectively. During periods of predawn low oxygen concentrations, the two pondway paddlewheels were shut down to temporarily maximize aerator oxygenation efficiency within the fish enclosures. Fish-feeding was restricted until sunrise or later, so that photosynthesis increased dissolved oxygen levels. Feeding was discontinued several hours before darkness so fish metabolism would decline before the nighttime algal respiration depressed oxygen levels.

At the beginning of each season, young tilapia and hybrid carp were moved from KST's geothermal well-water tanks where they had been overwintered. The young fish were stocked into the pondway at sizes ranging from 0.04 to 0.18 kg/fish (0.1 to 0.4 lb). Young tilapia became abundant throughout the pondway system due to natural spawning. These fish were very effective at consuming incoming particulates matter from the striped bass wastewater. The young tilapia could be collected throughout the summer at feeding station traps or trapped at warm-water inlets in late fall. KST produced a significant proportion of tilapia stock in this manner during the first two years of pondway use. Because of *Tilapia zilli* contamination, the pondway units were emptied in winter (slower growth rendered *T. zilli* undesirable).

Each enclosure contained multiple fish-holding sections—four in unit 1 and six in unit 2—providing for separation of tilapia and carp populations and, more importantly, allowing grading operations and fish-cohort separation. Continuous grading allows market-ready fish to be removed before their larger size negatively impacts system feed conversion efficiency. The primary market for

tilapia is as live fish; hence, fish size is very important to obtain best prices. The layout of the fish enclosures was designed to minimize harvest labor requirement and reduce fish handling stress. The enclosure concrete floor, shallow water depth, and inclusion of fish concentration zones allow for efficient, rapid, and safe daily loading of live fish onto waiting trucks.

The algal-based production system proved to be reasonably stable. Algae species dominance was observed to change during the season, shifting primarily from diatoms to green algae as water temperature increased. In spite of these changes there were only limited occasions when short periods of depressed algal productivity or algae die-offs impacted system performance during the three years of operation. At no time did algal events result in significant fish mortality. However, fish feeding was reduced for periods lasting as long as 1 to 2 weeks until normal algae densities could be reestablished.

After springtime stocking, pondway feeding rates began at 682 kg/d (1,500 lb). As water temperature increased, feeding was ramped up to 2,272 to 2,727 kg/d (5,000 to 6,000 lb) of total feed for both enclosures. Feeding rates were lower than added to tank-based systems and was spread out over more feedings per day to reduce oxygen demand and avoid low dissolved oxygen concentrations. The KST pondway/PAS systems produced tilapia yields of 17,727 kg (39,000 lb) in 2005; 60,454 kg (133,000 lb) in 2006; 69,900 kg (134,000 lb) in 2007; and 143,182 kg (315,000 lb) in 2008.

There are several advantages to the pondway approach, all resulting in more efficient fish production at lower cost. Many of the advantages are derived from confinement of the fish in a more manageable area so that the culturist can control the environment, accelerate growth rates, supplement oxygen levels, manage water quality, maximize feeding, improve feed conversion efficiency, treat disease, control parasites, eliminate bird predation, and manage fish size with grading, transfer, and harvest operations. The system also results in lower costs for utilities, chemical use, and water treatment to regulate pH, and less labor is needed for fish transfers and harvests. Likewise, there are cost advantages in treating the recycled water in pond systems as opposed to using more expensive filtration systems, including reduced costs of installation, operation, and maintenance. The pondway method is suitable for a wide variety of warm and temperate water fish species, including striped bass, catfish, tilapia, walleye, and many other candidate species.

During twenty-nine years of operation, KST utilized 26.5°C geothermal well water to grow tilapia, carp, catfish, and hybrid striped bass in approximately 100 concrete tanks on a year-round basis relying on a unique biological water treatment system recirculating 57,000 Lpm (15,000 gpm), or 80% of water needs. KST's staff of more than fifty employees produced and marketed over 50 million pounds of hybrid striped bass worldwide, and they sold several million pounds of tilapia and hybrid carp sold primarily to local markets. In 2006, as a result of increasing production costs and competition from imported frozen striped bass at US$3.30/kg ($1.50/lb), Kent SeaTech reduced hybrid striped bass production from 1.4 million kg/yr to 0.45 million kg/yr. At this time Kent began to increase pondway tilapia production. Unfortunately, at the same time,

imported frozen tilapia at US$1.32/kg began to appear in high volumes. Simultaneously, energy and feed costs rose dramatically.

In spite of improved economics of the pondway production system, in 2008, managers at KST decided that positive margins for fish sales in the United States were no longer possible. Consequently, the decision was made to alter Kent's business direction. In 2008, Kent SeaTech reemerged as Kent BioEnergy, transitioning to algae/aquaculture production for wastewater treatment and production of algae-based products including biofuels and biopower generation, animal and human food, pharmaceuticals, and other higher-value algal products.

13.8 References

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